A Hopping Robot for Planetary Exploration

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Abstract—This paper presents the design and some preliminary analysis of a hopping robot for planetary exploration. The goal of this project is to explore a different mobility paradigm which may present advantages over conventional wheel and leg locomotion. The approach is to achieve mobility by hopping and perform science and imaging via rolling. The device is currently equipped with a single video camera representing the science sensor suite. The hopper is equipped with a simple microprocessor and wireless modem so that it can receive sequences of commands and autonomously execute them, making it suitable for exploration of distant planets, comets and asteroids. One important feature of this hopper is that it uses a single motor for hopping in a specified direction as well as pointing the camera via rolling.

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1. INTRODUCTION

The best method to achieve mobility on Planetary Bodies is still the subject of discussion. So far, wheels have been used with excellent results for manned and unmanned mobility, and legged prototypes have been successfully demonstrated during Earth-based experiments. However, these are neither the only possible methods nor perhaps the most efficient ones to achieve mobility for exploration in low gravity (planets) and in micro gravity (small bodies) environments. Laboratory experiments have demonstrated the feasibility of slithering, rolling and hopping as alternate propulsion methods, thus paving the way to a more comprehensive approach to mobility than is currently considered. This paper describes the initial design and analysis of a small hopping robot whose mobility is achieved by a combination of rolling and hopping and rolling actions to first orient the body in the desired direction and then to jump forward towards the selected target. This approach extends previous designs by combining hopping and rolling mobility and by adding on-board computing, control, and sensing capabilities in a compact and lightweight device. The hopping robot proposed here is also intended as an experimental setup for under-actuated mechanisms, with the objective of studying the mobility characteristics achievable with the lowest possible number of actuators. A CAD model of the robot is shown in Figure 1.

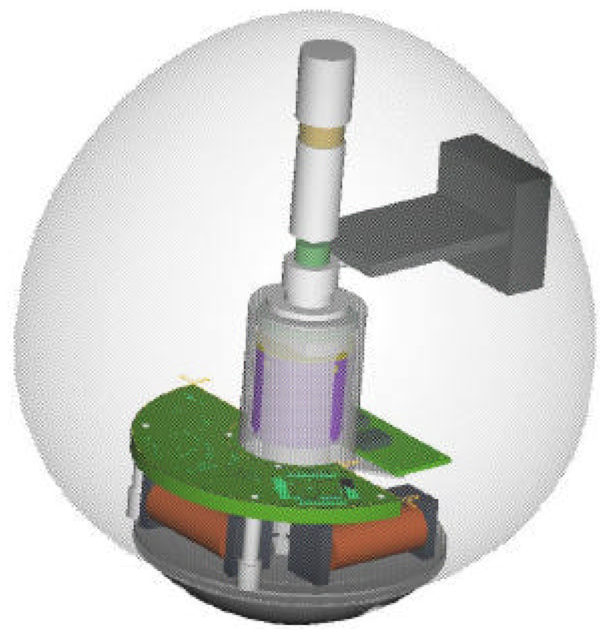

Figure 1: CAD rendering of the hopping robot

Hopping systems for planetary mobility were first proposed in [11,14] as a promising transportation concept for astronauts in a Lunar environment. A first order analysis of the performance of a Lunar hopper is presented in [5]. The authors propose a reference configuration consisting of a single-seat device propelled by a gas actuated leg hinged under the astronaut seat and stabilized by four elastic legs. The acceleration intensity and duration is limited by the tolerance of the human body. This design concept does not support the automatic reorientation of the hopper body, since the thrust leg can only rotate with respect to the main body about an axis normal to the pilot's plane of symmetry. A two-seat hopping laboratory is also briefly discussed, which is capable of changing direction during the acceleration and deceleration phases when the leg is in contact with the Lunar surface. The paper also includes the comparison among different approaches to Lunar transportation summarized in Table 1. The comparison is based on data from the Apollo missions, and subsequent studies and from the calculations presented in the paper. It shows that hopping is an efficient form of transportation in a low-gravity environment. More recently, a hopping robot, whose mechanical structure is the precursor of the device proposed in this paper, is described in [9]. The common characteristic of these two hopping systems is motion discontinuity, since a pause for reorientation and recharge of the thrust mechanism is inserted between jumps.

In general, however, laboratory demonstrations of hopping robots have focused on continuous motion and dynamic stability, without pauses between jumps. The seminal work in this area is summarized in [12], and analyzed mathematically in [6,7,8,10], among others, all discussing momentum imparted to the robot at lift-off with a suitable number of rotations of the lower link.

By necessity, the hopping robot described in this paper is different from the Acrobot, since any realistic planetary mission requires three dimensional motion, whereas the Acrobot's trajectory is limited to the plane of the links. In the paper we describe the main functions of the proposed system and summarize our initial analysis. The paper is organized as follows. Section 2 presents the system description. Section 3 summarizes a simplified model of the hopping robot and some initial simulations. Section 4 proposes a hybrid method for fine motion. Section 5 brifly summarizes our initial tests. Finally, Section 6 draws some conclusions from this work and discusses the directions of our future research and development.

Mobility	**Distance** (Km)	**Weight** (Kg)	**Payload** (Kg)	**Consumables**
Hopper	30	450	7	3 hours
Rocket	7	205	7	131 Kg of propellant
Rover	17	1750	larger	Several hours

Table 1: Comparison of Lunar Mobility Systems.

Marc Raibert's one-leg hopping robot. The simplest configuration of this robot consists of a thrust leg hinged at an actuated hip, as shown schematically in Figure 2-a. It has two active degrees of freedom (dof) represented in Figure 2-a by **x** the leg extension, and by **θ** the leg rotation with respect to the robot body. This robot can move at controlled speeds on a linear trajectory. A later model is equipped with an articulated hip enabling three-dimensional motion such as gymnastic jumps [4].

Current research on non-holonomic systems is motivating a renewed interest in the control of hopping robots. The device more often analyzed is the Acrobatic Robot, or Acrobot, a reversed double-pendulum with a single actuator located in the joint and free to move its base, as shown in Figure 2-b [1,2,3,13,15]. This device has only one active dof represented by **θ** in Figure 2-b. Reference [1] describes how to make the Acrobot jump by accelerating its center of mass, located in the upper link, until the base loses contact with the ground. The Acrobot configuration is similar to Raibert's early one-leg robot, with the single actuated joint acting as thruster and hip. The Acrobot attitude at landing is controlled by compensating the non-zero angular

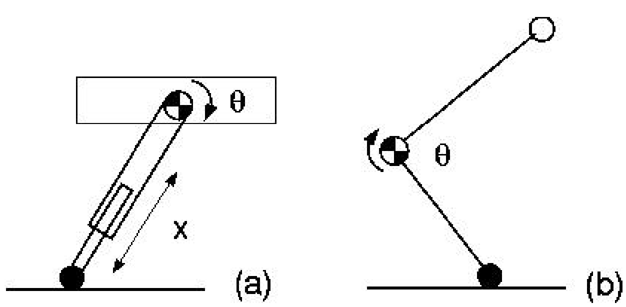

Figure 2: a. Raibert's hopping robot. b. The Acrobot

2. System Description

This section briefly describes the main components of the hopping mechanism and of its control and sensing electronics. The design is driven by the desire of minimizing the number of actuators, and the overall size and weight, while achieving useful scientific capabilities. Other design assumptions are (i) hard flat ground, (ii) static stability, and (iii) reorientation only at rest.

The Hopping Mechanism

The mechanical design for the hopper is an evolution of the Hoppet described in [9]. The hopping robot described here is designed as an exploratory device with a payload consisting of a few simple sensors and using hopping as its main mode of locomotion.

Several configurations were considered for the hopping mechanism, such as three-joint multiple leg and single leg devices. However, the first design would have required several actuators, and the second would have needed dynamical balancing. None of the approaches met our desire of a simple, small and lightweight design. The chosen mechanism is a robust egg-shaped body with self-righting capability. The hopping action is generated by a spring, which is loaded after each jump by a motor. The motor also provides the orientation of the body by rotating an off-axis mass towards the direction of the next jump. A possible drawback of this design is limited mobility on soft terrain, since the ground will conform to the shape of the robot and prevent it from self-righting. To overcome this possible problem, the center of gravity is positioned very low. Climbing hills may also pose some difficulty from the point of view of stability.

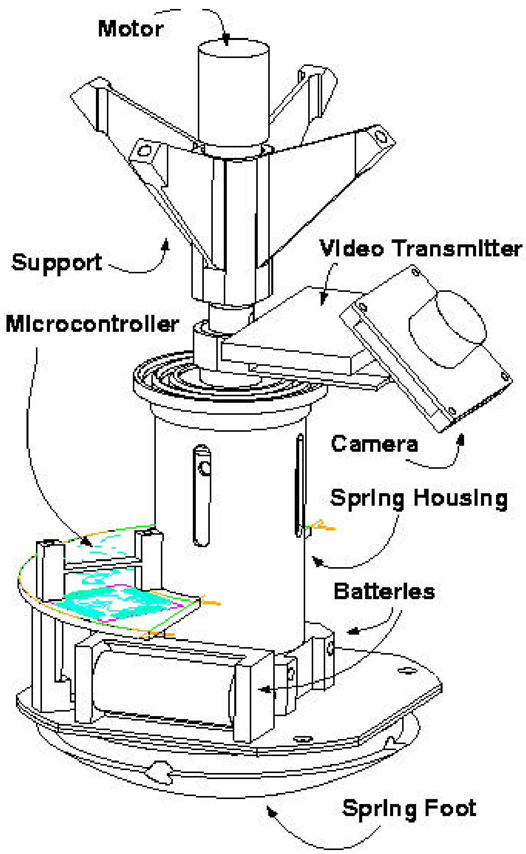

Figure 3: Schematic drawing of the hopping mechanism.

Figure 3 shows schematically the internal components of the hopping robot. The components marked by the arrows are the hopper foot, the electronic control board, the spring housing, and the camera/transmitter assembly. The mechanism is held in place by the external shell structure: the motor support is fixed to the upper shell, whereas the base plate of the mechanism is fixed to the bottom shell. The spring housing consists of two cylinders one inside the other. The internal cylinder protects the spring from contamination during extension. The external cylinder is fixed to the base plate and acts as a guide for the spring during extension and retraction. Pins fixed to the internal cylinder slide in the grooves of the external cylinder ensuring that the spring does not exceed its assigned range. The hopping action is initiated by commanding the motor to compress the spring. The spring is held in place by a lock-release mechanism consisting of a spring-loaded ball bearing, as shown in Figure 4. While compressing the spring, the motor also moves downwards a small cylinder to trigger the spring release mechanism. The trigger presses against the lock-release bearing after a fixed stroke determined by the mechanism design. This releases the balls and frees the internal cylinder, which starts the extension of the hopping spring.

After the robot has landed, the spring is retracted until the internal cylinder locks into the bearing, making it ready for a new compression. During the retraction of the spring, the

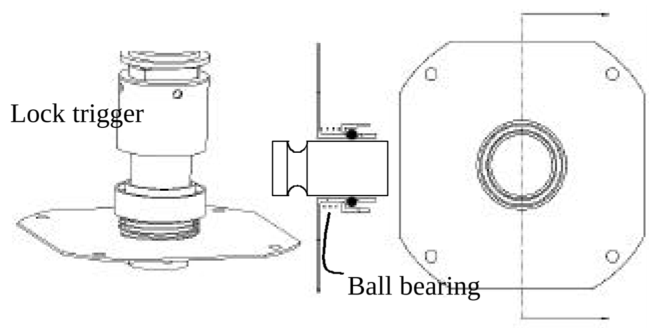

Figure 4: Drawings of the locking mechanism

motor rotates the camera and transmitter assembly, which act as an eccentric mass attached to the motor shaft. Their angular position determines the leaning direction of the robot, and therefore the direction of the subsequent jump. On a hard floor, this approach allows hopping in the plane identified by the vertical axis and the mass position. A one-way, over-running clutch is used to rotate the mass only in the counter-clockwise direction. In this way the mass can be positioned in the desired direction during the spring retraction. It remains in place during spring compression, since the clutch lets the motor shaft rotate freely in the clockwise direction.

The egg-shaped robot body consists of a shell made of transparent polycarbonate. The shell is divided transversally into two parts for ease of assembly, provides protection and support for the internal components. The top half of the shell is clear to allow the instruments to view the environment.

The motor is powered by a 12 V DC supply at 100 to 300 mA provided by four primary batteries located on the base plate of the mechanism. A 66:1 gear reduction produces 0.1 Nm of torque, sufficient to compress the spring. The screw has 90% efficiency and generates 500 N. The spring constant is approximately 2 Kg/mm and the spring is compressed about 20 mm.

Figure 5: Testing configuration of the hopping robot.

Figure 5 shows the assembled prototype during our initial tests. The motor assembly and the camera arm are visible through the transparent top shell.

Computer and Sensor Electronics

The controller must be able to support autonomous navigation, science acquisition and communication with other units. Furthermore, it must have very low power consumption to increase operational time and minimize weight. To achieve these objectives, we are utilizing the small microcontroller board developed at JPL. This board performs motor control and sensor acquisition tasks. The micro-controller on the board is powerful enough to support the basic functions of the current prototype. Future increases in computational requirements will be satisfied by using additional boards.

The microcontroller is based on the PIC16C65A processor, a CMOS chip, and consists of a 2.5 x 9 cm circular board with motor controller circuits, a serial port, analog and digital I/O and analog signal conditioning. The serial port can be programmed to implement the I^2C protocol, thus providing the robot with a low power, multi-master, multi-drop serial bus. This protocol is well suited to implement a low speed (100 Kbit/second) serial bus supporting a multi-processor architecture, since it significantly reduces the mass of the cabling interconnection. A standard RS232 serial port can also be activated by software, to enable the communication with an external terminal. The motor controller is the HP HCTL1100, which implements a digital PID algorithm to control motor velocity and position. All the major board components have power-down features which are used for power management of the electronics. The power consumption of the board is approximately .35 W, excluding motor and science instruments. Communication with an operator and other robots will be carried out with an RF modem currently under development.

In the future, the robot will be powered by a panel of solar cells located on the top part of the shell and by rechargeable batteries located in the base. Currently, the robot power is provided by four Panasonic primary batteries. Each battery has an output voltage of 3 V and a maximum current of 300 mA.

The instrument suite of this first prototype consists only of a video micro-camera coupled with a transmitter to convey remote images to an operator. The camera operates at 12 V DC and 175 mA, and the transmitter at 12 V DC and 100 mA. The transmitter sends streaming video on the amateur band occupied by channel 14. Clearly, this video system is large and power hungry (over 3 W), but in the future, smaller Active Pixel Sensor cameras could be used to reduce size, mass and power consumption. The camera is installed on the arm and is rotated about the robot main axis in the counterclockwise direction during the retraction of the thrust spring. This setup allows the dual function of re-orienting the robot body by rotating the camera arm and

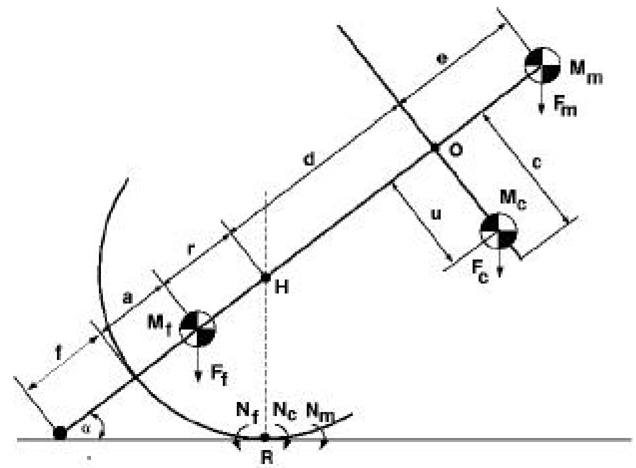

Figure 6: Model of the hopping robot.

of taking a panoramic view of the terrain surrounding the robot.

3. Static and Dynamic Models

The modeling and analysis carried out for this prototype have been primarily concerned with the static stability of the system, to ensure that the design requirements of self-righting and orientation can be met. To simplify the analysis, we consider the two-dimensional model shown in Figure 5. Here, the hopping robot is represented by three masses: M_f, M_m, and M_c, representing the mass of the spring and foot mechanism, of the motor, and of the camera arm, respectively.

The control input to the system is the position u of the camera mass, M_c, on the support arm, assuming that, in this simplified model, M_c can be moved up and down the arm. Therefore the control input is ($-c \leq u \leq c$), with c being the length of the camera arm.

The mass distribution required to have the hopping robot lean at an angle α on its side is given by:

$$F_f\ r\cos a = F_m(d+e)\cos a + F_c(d\cos a + u\sin a) \quad (1)$$

where F_c, F_f and F_m represent the force applied by the camera body, the foot and spring mechanism, and the motor, respectively. The other model parameters indicated in Figure 5 are: *a* is the distance from the bottom of the foot to the center of mass M_f, *(r+a)* is the radius of the hemispherical bottom, *(d+r+a)* is the distance form the camera arm attachment to the foot bottom, and *e* is the distance from the camera arm attachment to the center of mass M_m. The numerical values of these parameters are as follows: M_f = 575 g including lower shell, batteries, foot, spring assembly, and electronics; M_m = 200 g including upper shell, motor, bracket, and bearings; M_c = 65 g including camera, camera mount, arm, and transmitter; *a* = 30 mm, *(r+a)* = 80 mm, *(d+r+a)* = 100 mm, *c* = 45 mm, *e* = 50 mm.

The critical design constraint required to achieve maximum hopping distance, i.e. $\alpha = 45^o$ and u = c, is satisfied when:

$$1.3\,F_c = F_f - 1.4\,F_m \qquad (2)$$

which is used to compute the balancing weight on the camera arm.

The dynamic operation of the robot relies on the assumption that the ground friction can withstand the force applied by the spring. This may not always be the case, or it may happen that the friction cone of the surface material has a narrower angle than the direction of the applied spring force. The robot foot is covered with a high-friction material to avoid slipping. However it is quite unlikely that the robot will be able to take off at the optimal 45^o angle, and higher angles within the surface friction cone will be used. A second factor affecting the take-off angle is the self-righting effect of the spring force about the contact point **R**. To overcome this torque, the robot foot is designed with a small protrusion at the center, represented schematically in Figure 6 by segment *f*. This extension prevents the robot from rotating about **R** on a hard floor, and orients the floor reaction force towards the center of gravity of the body. This is important to reduce the angular momentum imparted by the spring force to the robot body at take-off. There is no static load on the tip of protrusion *f*, since equation (2) is still used to balance the body at rest.

4. Large and Fine Motion

We plan to achieve the mobility of the hopping robot prototype mostly by jumping in the direction of a target specified by the operator. However, because of the fixed load of the spring, there will be no adjustment possible on the length of the jump. Furthermore, the uncertainty of the terrain condition and of the lift-off angle will prevent the advanced calculation of the trajectory parameters.

To cover short distances and to approach the desired target, we are planning to develop and test two new methods for fine motion control of the hopping robot. The first will consist of two lateral jumps, such that the base of the resulting isosceles triangle is the desired distance. On a hard terrain, it will be possible to move the hopper with higher accuracy by rolling it on its base, as an eccentric spherical wheel. Unfortunately, both methods will only be carried out in open-loop control, since the camera will not be able to track the target during motion, and therefore will not provide any visual feedback.

5. Initial Tests

Preliminary laboratory demonstrations have shown that the robot is capable of performing short jumps on a flat floor. With the current set-up, the robot can travel approximately 20 cm in the direction pointed by the camera. Although only qualitative, these tests are identifying a number of limitations of the current design, in particular with respect to the mechanical losses in the spring assembly. The design calculation predicted a much longer hop range than it is possible to achieve. Furthermore, the structural load on the shell and the friction of the lock-release bearing on the spring cylinder greatly reduce the force available to accelerate the robot.

In the final configuration, the operator will command the robot by simply pointing the camera to the desired direction, and then issuing a jump command, leaving the robot orientation control and jump execution to the on-board processor.

6. Conclusions

This paper describes the prototype of a hopping robot suitable for simple exploratory missions in low gravity environments. The robot consists of an egg-shaped shell enclosing a thrust mechanism, power storage devices and control and sensing electronics. The hopping robot is designed as an autonomous robot, capable of autonomous navigation and scientific data acquisition. Mobility is achieved by hopping in the direction of a suitable target, and data collection is currently represented by a video camera transmitting a video stream to a controlling computer. Hopping is powered by a spring released under computer control, whereas orientation is achieved by rotating an off-axis mass, consisting of the video camera and its transmitter, about the robot vertical axis. By using a uni-directional bearing, the robot achieves mobility and orientation with a single actuator. Control is carried out by an on-board micro-controller communicating with the control station using a wireless modem. In the future, we plan to carry out extensive simulations and experiments with the prototype to test its mobility capabilities and fully develop a new method of fine motion control based on hopping and rolling.

7. Acknowledgment

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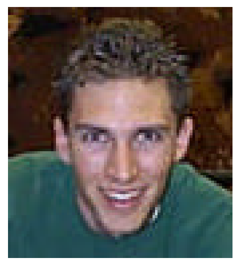
Paolo Fiorini holds a Laurea degree in Electronics Engineering from the University of Padua, Italy , an M.S. in Electrical Engineering from UCI, and a Ph.D. in Mechanical Engineering from UCLA . Since 1985 he has been at NASA-Jet Propulsion Laboratory, California Institute of Technology, where he is currently a Member of Technical Staff in the Telerobotics Research and Applications Group. Dr. Fiorini has published several papers in the areas of telerobotics systems and control, human-computer interfaces, motion planning of autonomous vehicles, and control of time-delay systems. He has been the recipient of ten NASA technical awards and he is a Senior Member of the IEEE.

Samad Hayati works at Jet Propulsion Laboratory in Pasadena California where he is the technical manager of the Long Range Science Rover and the Rendezvous and Sample Retrieval tasks for the Mars Sample Return Mission. Samad has M.S. and Ph.D. in Mechanical Engineering with a specialty in controls from the University of California at Berkeley. Since 1979 he has been with the Jet Propulsion Laboratory working first on the guidance and control of the Galileo spacecraft, and since 1983 performing research in robotics at JPL. He has published numerous conference and journal papers and holds two US patents related to robotics control. His pioneering work in robot calibration was used to develop techniques to utilize manipulators as an aid in brain neurosurgery at the Long Beach Memorial Hospital in California in 1986.

Matt Heverly is completing his undergraduate degree in Mechanical Engineering at the California Polytechnic University in San Luis Obispo. His work on the mechanical design of the Hopper was done as an internship project at JPL. He has worked on mechanical prototype designs at JPL in the past and hopes to continue work in the aerospace field after graduation.



Jeff Gensler is a Senior in Mechanical Engineering at The University of Texas at Austin. Although a continuing student, he has over a year of working experience at the Jet Propulsion Laboratory in Pasadena, CA. He has worked on many projects at JPL including Mars Pathfinder and the next generation of rover missions to Mars. His soil mechanics analysis from Mars Pathfinder was published in *Science* magazine along with the official science report. Jeff is planning to graduate in Summer 2000 and then attend graduate school. His hobbies include computers, radio controlled aircraft, and outdoor activities.